X-Ray Bursts and Millisecond Oscillations in the Millisecond X-Ray Pulsar SAX J1808.4-3658

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Millisecond Variability in Low-Mass X-Ray Binaries

1. Kilohertz quasi-periodic oscillations (kHz QPOs)
   - QPO pairs with roughly constant frequency separation (~300 Hz)
   - QPO frequencies drift by hundreds of Hz as X-ray flux changes
   - Particular separation frequency is a characteristic of a given source
   - Seen in over 20 LMXBs. Believed to originate in accretion disk.

2. X-ray burst oscillations
   - Nearly coherent msec oscillations during thermonuclear bursts (270-619 Hz)
   - Frequency drifts by several Hz during burst, reaching an asymptotic maximum that is a characteristic of a given source. Interpreted as angular momentum conservation in decoupled burning layer on rotating NS (Strohmayer et al. 1997; Cumming & Bildsten 2000).
   - Seen in 10 sources, over 100 examples (e.g. Muno et al. 2002); most are also kHz QPO sources
   - Amplitude evolution in burst rise interpreted as spreading hot spot on rotating NS. Oscillations in tail not well understood.
   - "Nuclear-powered" pulsars?

3. "Bona fide" accretion-powered millisecond X-ray pulsars
   - Four sources known, all X-ray transients in very compact binaries
   - Pulsed amplitude ~5%, why not detected in other LMXBs?

(1)+(2) often seen together, but neither seen together with (3). Thus, relationship with spin not proven directly.

Relationship Between Burst Oscillations and kHz QPOs

The separation frequency $\Delta\nu_{kHz}$ organizes the burst oscillation sources into two groups:

- <u>"Slow" oscillators (~300 Hz):</u> $\nu_{burst} \approx \Delta\nu_{kHz}$
- <u>"Fast" oscillators (~600 Hz):</u> $\nu_{burst} \approx 2\Delta\nu_{kHz}$

Photospheric radius expansion properties also divide along these lines, with fast oscillations usually occuring in radius expansion bursts. (Muno et al. 2000)

Which is spin frequency, ν_{burst} or $\Delta\nu_{kHz}$? Factor of two ambiguity.

<u>kHz QPOs</u>: (1) Beat frequency interpretation (e.g. Miller, Lamb, & Psaltis 1998)
Lower kHz QPO = beat between Keplerian and spin frequencies. Requires special burst ignition properties for fast oscillators. Why is everything spinning at ~300 Hz?

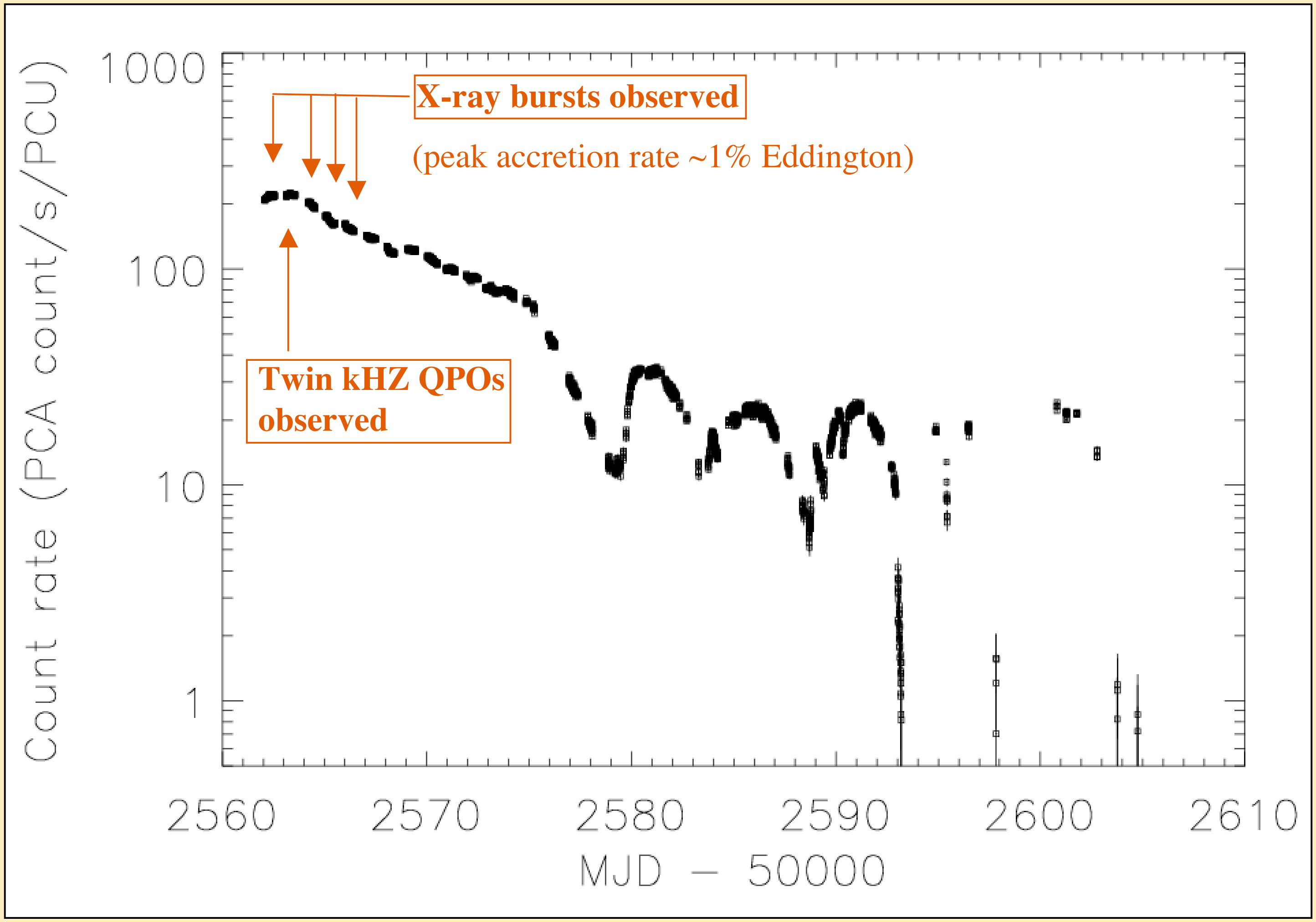
(2) Relativistic precession interpretation (e.g. Stella & Vietri 1999)
Lower kHz QPO = GR precession mode frequency for free-particle orbit at preferred radius. Relationship to burst oscillation not explained in this picture with additional assumptions.

In both interpretations, upper kHz QPO is Keplerian frequency at "preferred" accretion disk radius

X-Ray Outburst History of SAX J1808.4-3658

- 1996 September (BeppoSAX)
  - Source discovered by BeppoSAX/WFC (in 't Zand et al. 1998)
  - Thermonuclear bursts observed.
  - Marginal detection of 401 Hz burst oscillation in later reanalysis (in 't Zand et al. 2001)
- 1998 April (RXTE)
  - 401 Hz persistent pulsations (Wijnands & van der Klis 1998)
  - 2 hr binary orbit (Chakrabarty & Morgan 1998)
  - Mass donor is a hydrogen-rich ~0.05 $M_\odot$ brown dwarf (Bildsten & Chakrabarty 2001)
- 2000 January (RXTE)
  - Emerged from behind Sun in low, flaring state (Wijnands et al. 2001)
- 2002 October (RXTE)
  - Outburst detected early (Markwardt, Miller, & Wijnands 2002)

2002 Outburst Flux History for SAX J1808.4-3658



700 ksec total: unprecedented coverage of the decay of a soft X-ray transient

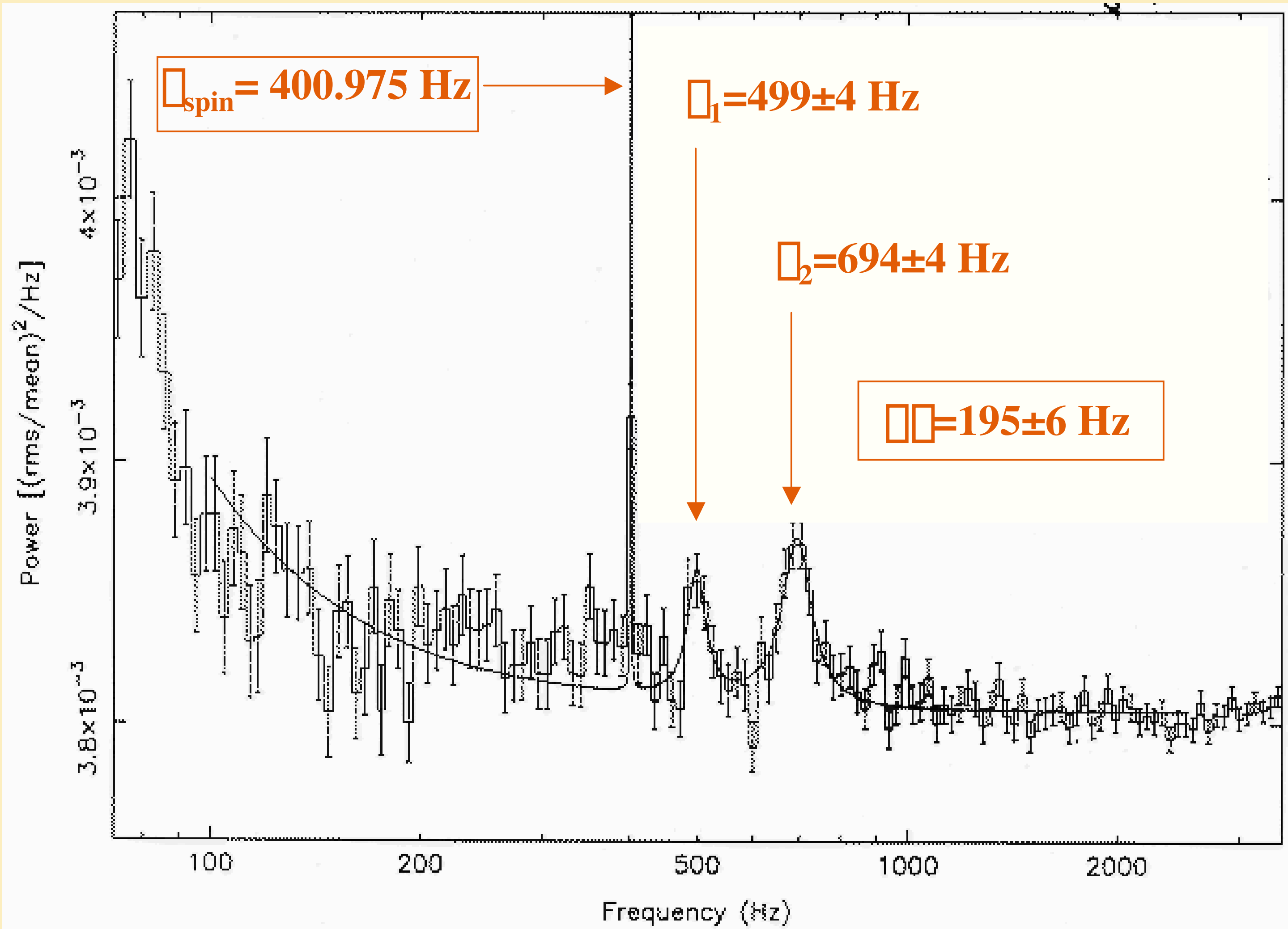
Executive Summary of 2002 Outburst Results for SAX J1808.4-3658

- $\nu_{burst} \approx 400$ Hz (Chakrabarty et al. 2003)
- $\Delta\nu_{kHz} \approx 200$ Hz (Wijnands et al. 2003)
- $\nu_{spin} \approx 400$ Hz (Morgan et al. 2003)

Upper limit on amplitude of a persistent pulsation at 200.5 Hz is $<0.014\%$, establishing the spin frequency as 401 Hz.

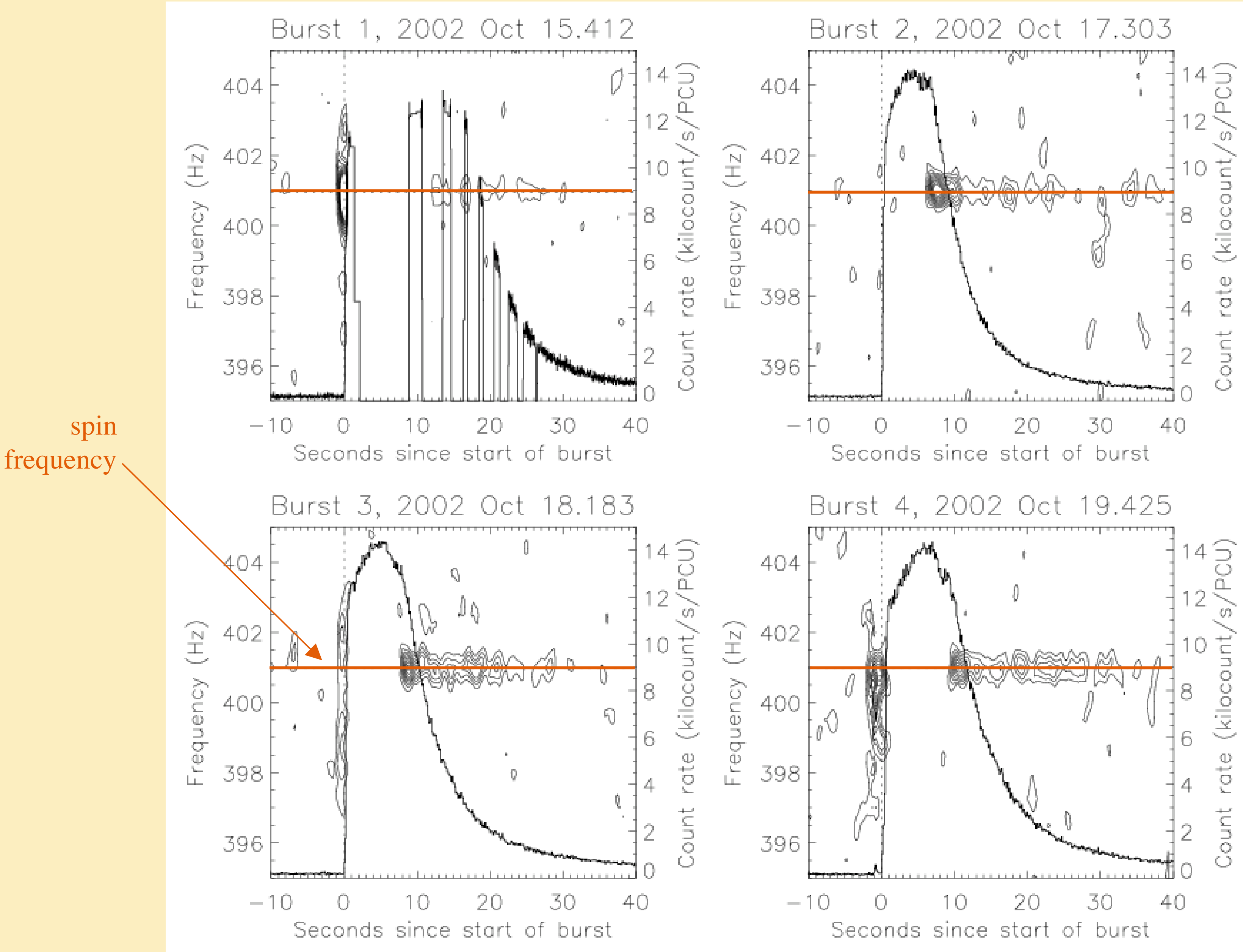
Kilohertz QPO Pair in SAX J1808.4-3658

2002 October 16 data (near peak of outburst)



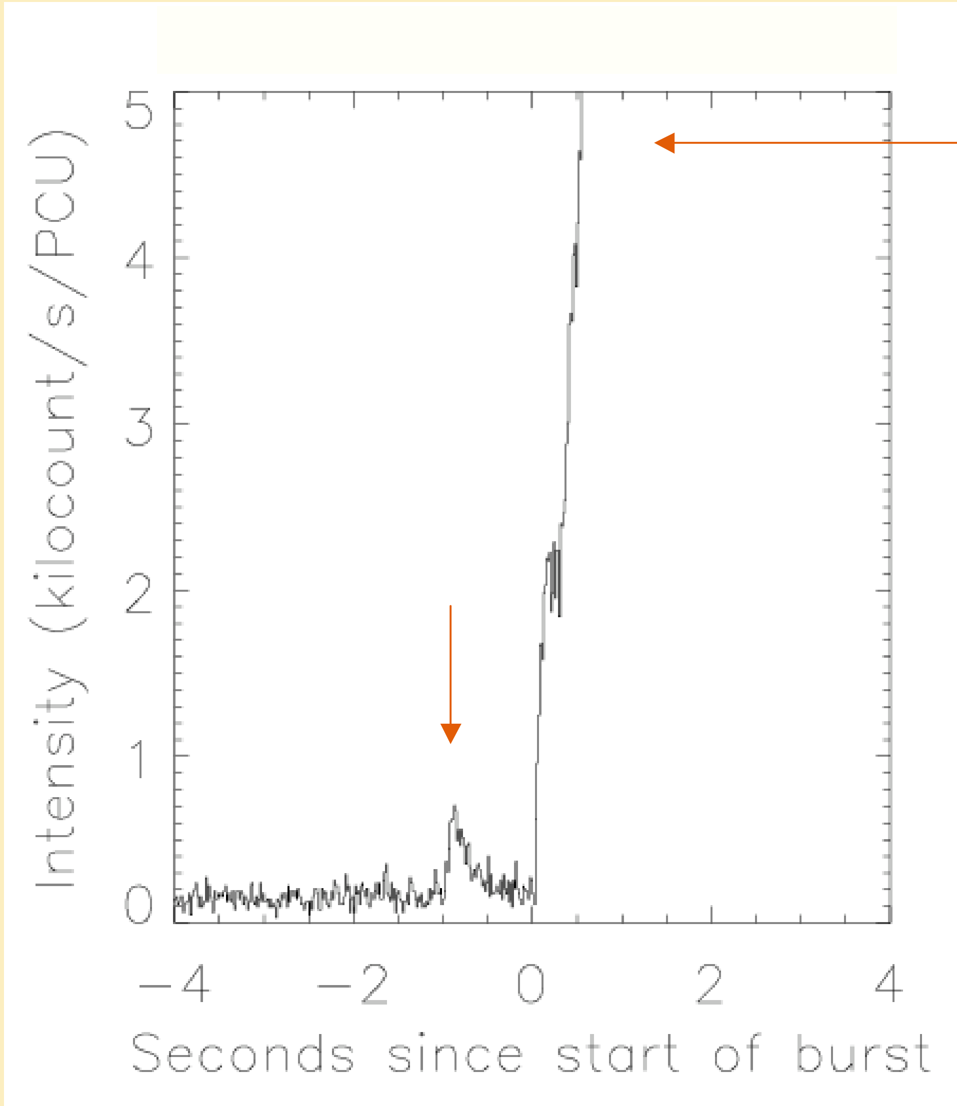
Wijnands et al. 2003

X-Ray Burst Oscillations in SAX J1808.4-3658



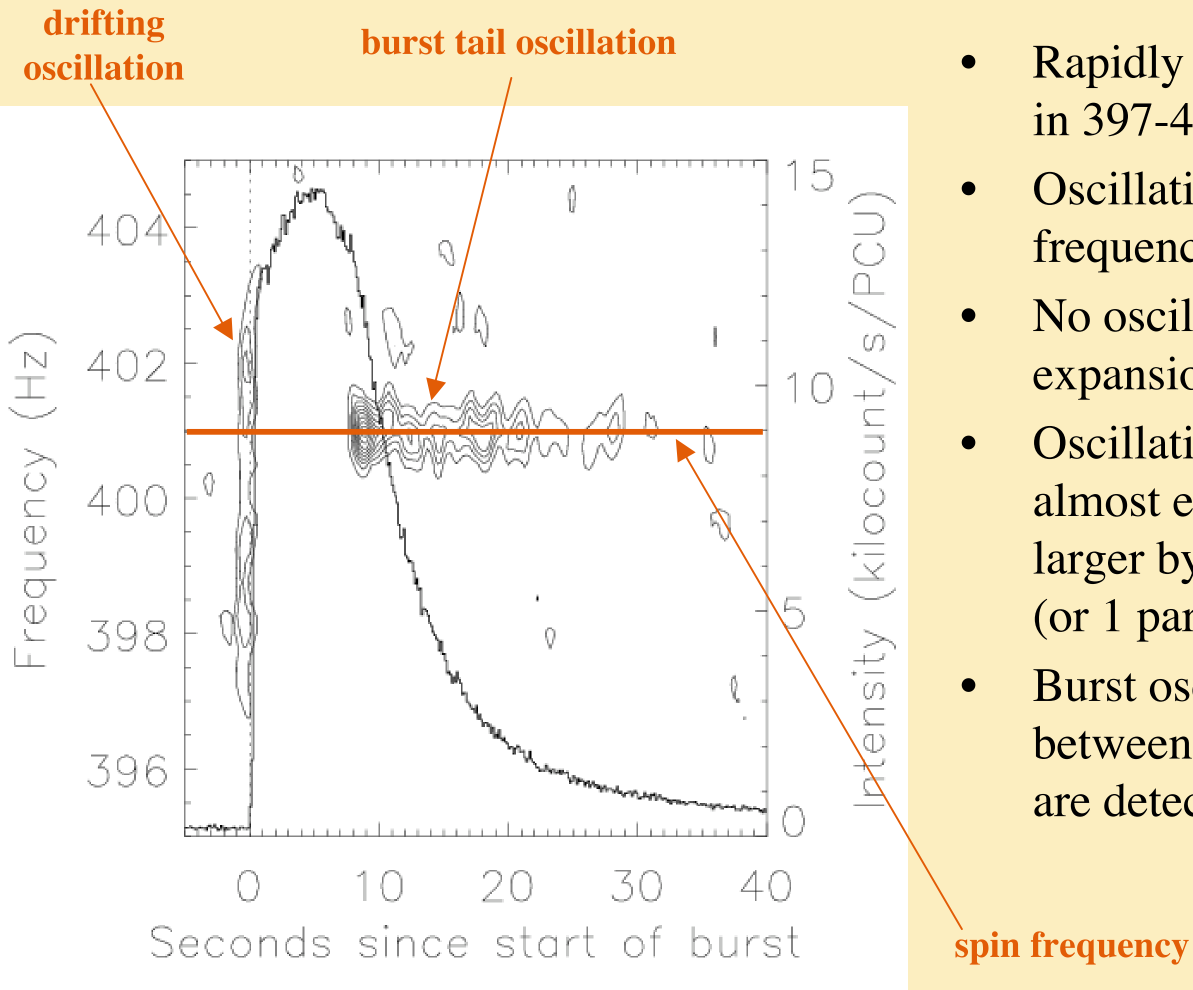
Chakrabarty et al. 2003

Small precursor to Burst 4 on 2002 Oct 19.4
(SAX J1808.4-3658)



Peak count rate of main burst ~14 kcount/s/PCU

X-Ray Burst Oscillation in SAX J1808.4-3658: detail

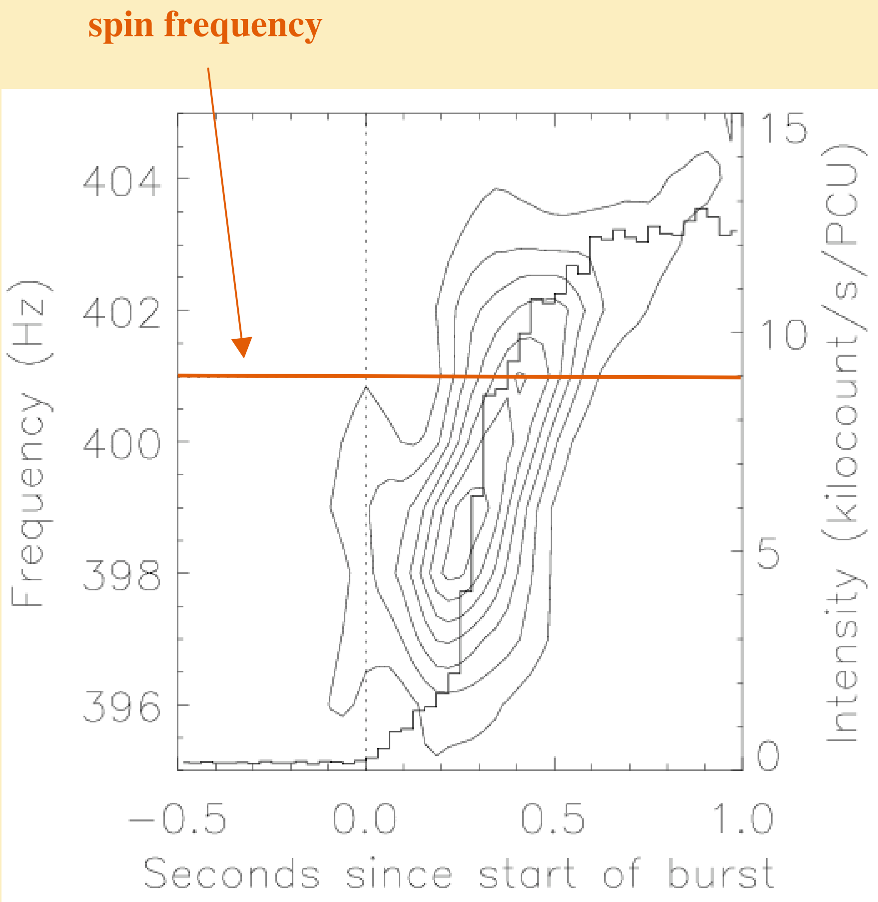


Burst 3
2002 Oct 18.183

Chakrabarty et al. 2003

- Rapidly drifting oscillation in burst rise in 397-403 Hz range
- Oscillation overshoots the spin frequency during the burst rise.
- No oscillation detected during radius expansion phase of burst
- Oscillations reappear in burst tail at almost exactly the spin frequency, but larger by 6±1 mHz, which is 0.0015% (or 1 part in 67000) difference.
- Burst oscillation amplitudes vary between 3% and 5%. No harmonics are detected (<0.5%).

Rapid drift of oscillation during burst rise in SAX J1808.4-3658



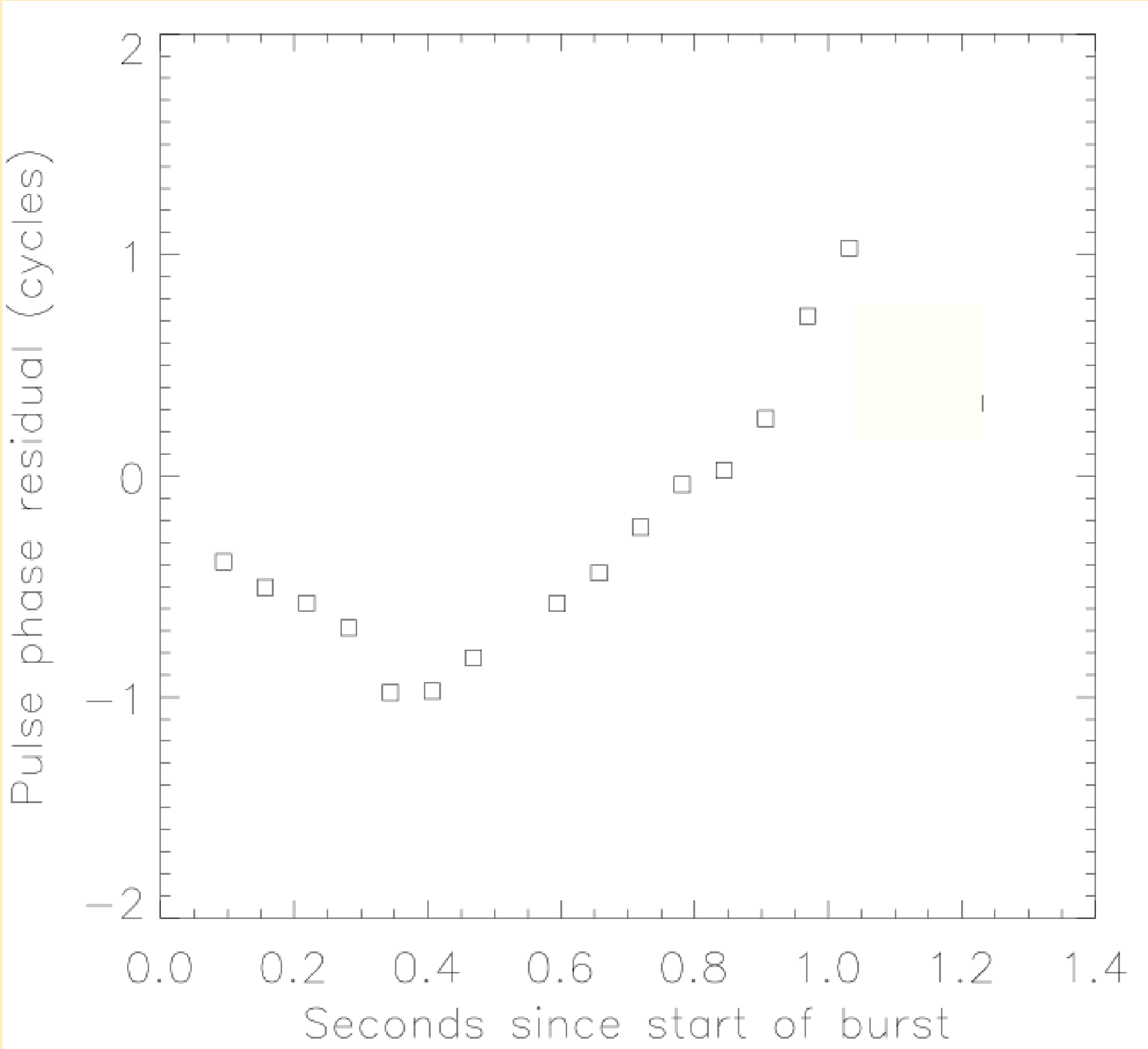
Chakrabarty et al. 2003

- Drifting oscillation is evidently similar phenomenon as seen in other 10 burst oscillation sources, where drift is interpreted as angular momentum conservation in a decoupled burning layer.
- Oscillation drifts rapidly during the burst rise, changing by around 5 Hz in around 0.5 s.
- This drift time scale is shorter by an order of magnitude compared to other sources.
- Phase connection indicates smoothly varying oscillation.

Phase connection of oscillation during burst rise in SAX J1808.4-3658

Burst 3
2002 Oct 18.183

Independent phase residuals relative to constant frequency model at 400.9752 Hz



Chakrabarty et al. 2003

Consistent with a single, smoothly drifting burst oscillation

Rapid drift in SAX J1808.4-3658: magnetic field effect?

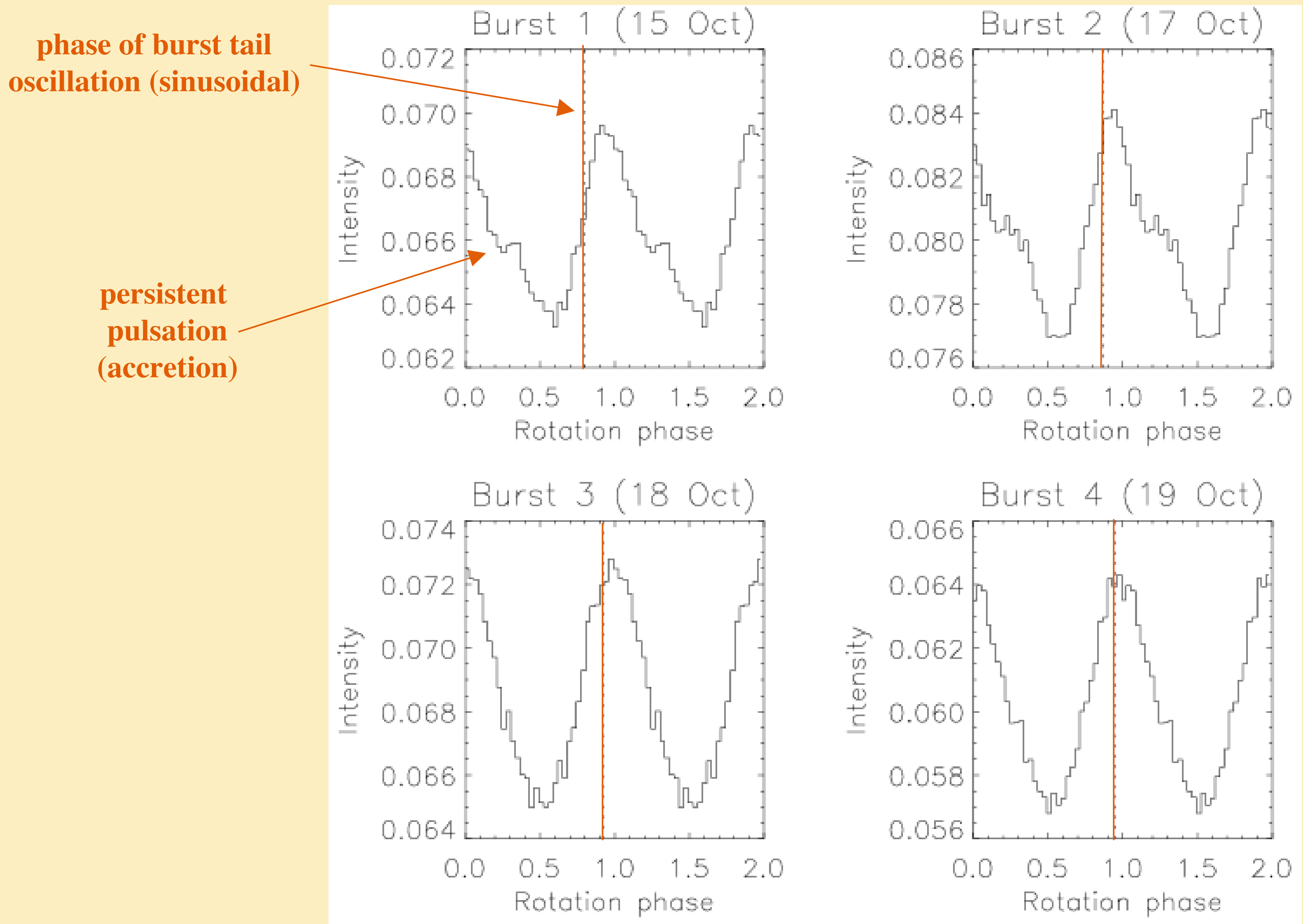
- Cumming & Bildsten (2000): sufficiently strong magnetic field may prevent rotational shearing in burning layer (i.e. when $B^2/8\pi$ is comparable to the shear energy), leading to small (or zero) frequency drift.

- Our slightly modified idea: the magnetic field provides a restoring force that acts to counter the shear, leading to a more rapid drift. We thus interpret the comparatively rapid drift in SAX J1808.4-3658 as evidence of a stronger magnetic field than other burst oscillation sources.

- SAX J1808.4-3658 is only persistent pulsar among the burst oscillation sources. Others may have fields too weak to channel accretion flow. Compare proposal of diamagnetic screening of field by accreted material for high accretion rates (Cumming, Zweibel, & Bildsten 2001). (But, why are spectra similar?)

- If most burst oscillation sources have weaker magnetic fields, then they are unlikely to show persistent pulsations down to very low amplitudes.

Phase relationship of burst tail oscillations and persistent pulsations in SAX J1808.4-3658



Chakrabarty et al. 2003

The oscillations in the burst tail always have the same rotational phase!
They lead the persistent pulsations by about 10%.

Rotational phase-locking of burst tail oscillations in SAX J1808.4-3658

- The burst tail oscillations must be associated with the NS surface.

- The emitting hot spot in the burst tail "knows" about the NS magnetic field and probably has a nearly fixed orientation with respect to the magnetic poles.

- The 11% phase offset with respect to the persistent pulsations is consistent with the phase drift accumulated over the duration of the burst tails due to the slight (<0.002%) frequency difference. This requires an initial phase alignment in the burst tail followed by a slight motion of the hot spot (e.g. Spitkovsky et al. 2002; Heyl 2001).

Energy dependence of oscillations and pulsations

- Most burst oscillation sources (Muno et al. 2003)
  - Pulse amplitude increases with energy
  - Hard pulses lag soft pulses

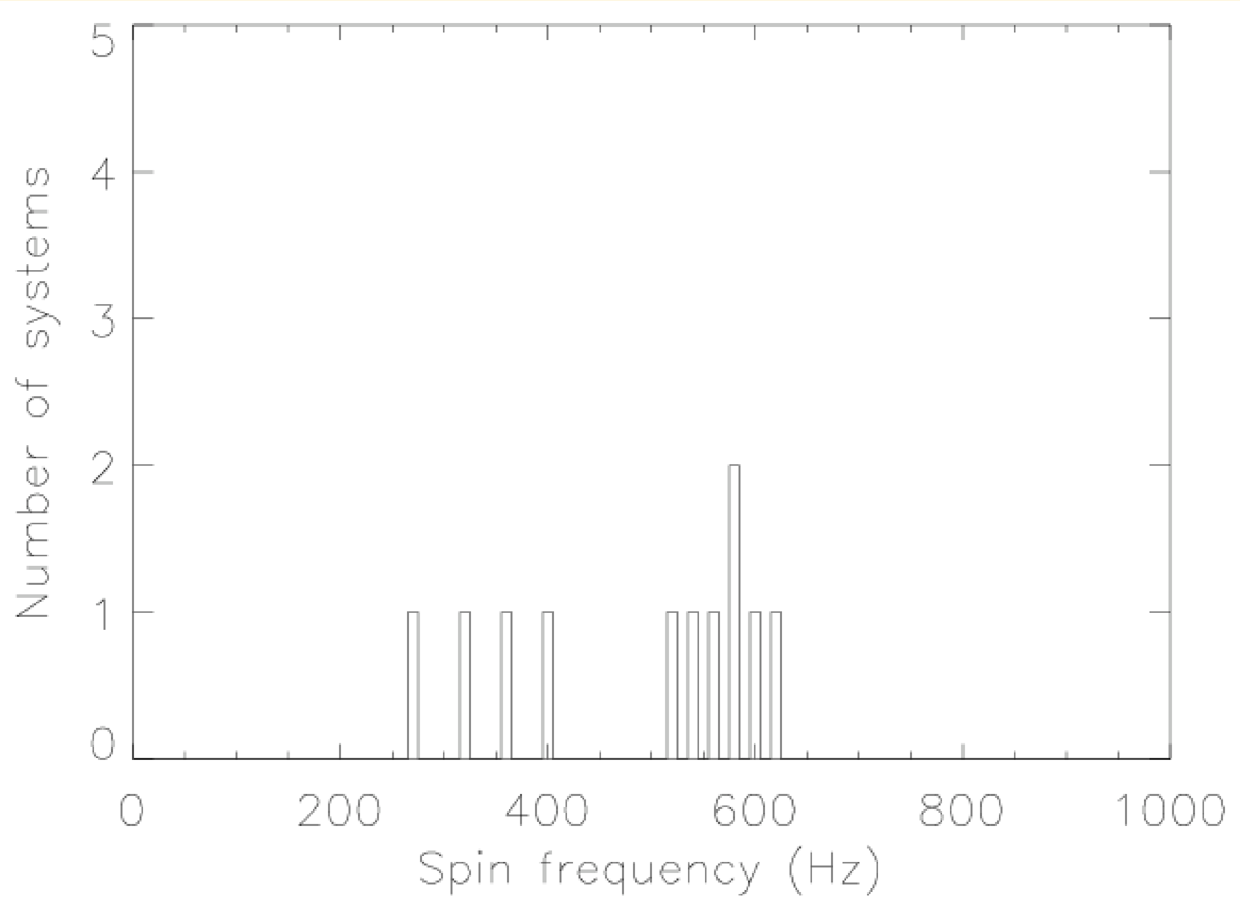
- Persistent millisecond pulsations (SAX J1808.4-3658 and XTE J0929-314; Cui et al. 1998; Galloway et al. 2002)
  - Pulse amplitude decreases (slightly) with energy
  - Hard pulses precede soft pulses

- Burst oscillations in SAX J1808.4-3658 (preliminary!)
  - Pulse amplitude roughly constant with energy
  - No clear pattern in phase vs energy
  - Further analysis in progress

Burst Oscillation Frequencies

4U 1916-05	270 Hz
4U 1702-429	330 Hz
4U 1728-34	363 Hz
SAX J1808.4-3658	401 Hz
KS 1731-26	524 Hz
Aql X-1	549 Hz
X1658-298	567 Hz
4U 1636-53	581 Hz
X1743-29	589 Hz
SAX J1750.8-2900	601 Hz
4U 1608-52	619 Hz

Distribution of Burst Oscillation Frequencies



Summary

- X-ray bursts in SAX J1808.4-3658 occur in a relatively unexplored low-$\dot{M}$ regime.
- Thermonuclear X-ray burst oscillations trace the spin of accreting neutron stars: **nuclear-powered millisecond pulsars**.
- We do not understand the origin of kilohertz QPOs.
- The magnetic field strength of the millisecond X-ray pulsar SAX J1808.4-3658 is evidently stronger than that of the other (non-pulsing) burst oscillation sources.
- Oscillations in the burst tails of SAX J1808.4-3658 are somehow tied to the magnetic field geometry of the neutron star.
- The spin frequency distribution of nuclear-powered millisecond pulsars cuts off sharply at the high end.